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K.P. Ziock, B. Pohl, G. Schmid, C. Cork, E. Hull, P. Luke, N. Madden

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K.P. Ziock, B. Pohl, and G. Schmid
Lawrence Livermore National Laboratory
P.O. Box 808, Livermore, CA 94551

C. Cork, E. Hull, P. Luke, and N. Madden
Lawrence Berkeley National Laboratory
1 Cyclotron Road, Berkeley, CA 94720

Abstract

The advantages of spectrally resolved gamma-ray imaging have previously been demonstrated for the detection of fissile materials. However, previous results have been obtained with the relatively poor spectral resolution provided by scintillator-based detectors. In this paper we present a new class of coded aperture imager based on a position-sensitive germanium detector. The use of this detector type provides a factor of 40 improvement in energy resolution which improves the quality of the images obtained while reducing the integration time required. Tight spectral cuts on known emission lines allow deeper penetration into highly attenuating objects. In addition, advanced analysis techniques can provide information on overlying material through the application of spatially resolved gamma-gauging. We describe the imager, present simulations of its capabilities and the first characterizations of a prototype detector.

Introduction

The use of gamma-ray detectors for control of fissile material is a well established technique. The detectors take advantage of the penetrating gamma radiation emitted by all of these materials and are used in almost all areas involving control of fissile material. Over the past decade, a new class of gamma-ray instrumentation has been developed which takes advantage of the directional nature of the radiation to generate images.[1-3]

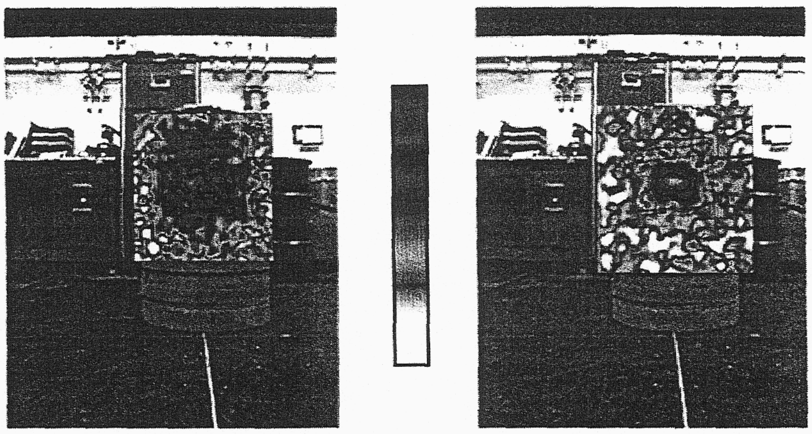

Figure 1. Gamma-ray images cut on elemental energy lines of Pu (right) inside a storage drum taken through 3 mm of depleted uranium (left). The rectangular structure of Pu rods is clearly visible through the overlying materials.

As with non-imaging instruments the addition of energy resolution to an imager enhances its performance as has been demonstrated with the current alkali-halide, scintillator based systems.[1,2] Even the modest energy resolution of these instruments has demonstrated the advantages of spectral information in a number of applications including possible uses in transparency and diagnostics[4] and at uranium enrichment plants.[5] The spectral information allows one to both identify isotopes in the image and to see through overlying material (see Fig. 1).[1] As is the case with non-imaging instruments, significant performance gains can be realized if one improves the energy resolution of the detector. To this end we are developing a portable, coded-aperture imager based on a position-sensitive, germanium detector.

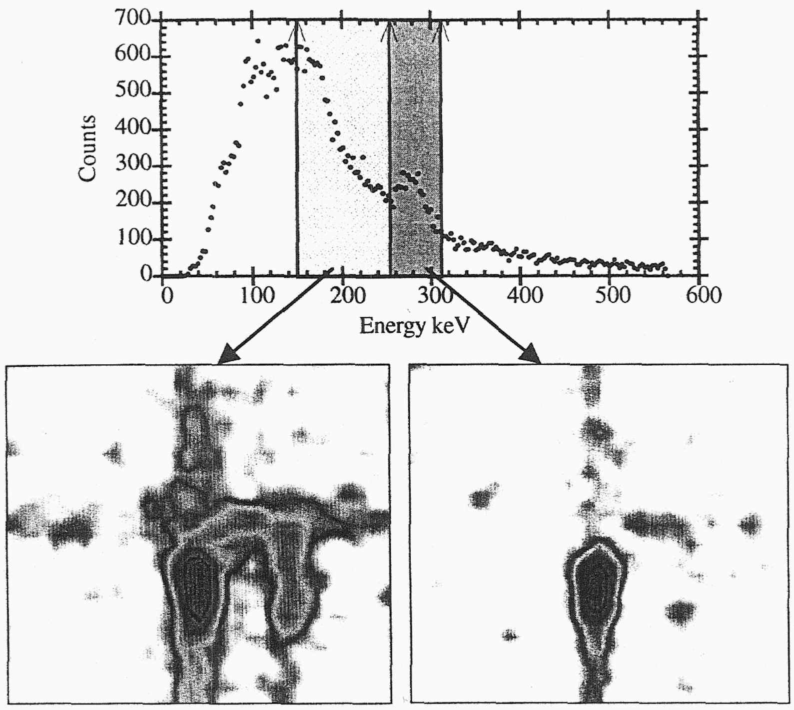

Figure 2. Gamma-ray images from the K25 diffusion plant. A deposit in process piping contains Np which can be localize by placing energy cuts based on the darker shaded region of the spectrum (right image). The colors are the inverse of the color bar in Figure 3.

Performance Improvements
With over an order of magnitude improvement in energy resolution beyond current instruments, a germanium-based, coded-aperture imager represents a significant advance in capabilities. Tight cuts on emission lines will allow one to improve contrast for isotope specific images by reducing background from other isotopes and Compton scattered radiation from the object itself. Consider the energy spectrum associated with figure 2.[4] This is an image taken in the K-25 gaseous diffusion plant where reactor products fed back into the cascaded produced neptunium contamination. If the gamma-ray image is generated using only radiation in the shaded region of the spectrum, then one clearly sees that the Np is concentrated in the deposit dominating the image (right image). However, as can be seen from the spectrum, even the best energy cuts include continuum radiation estimated at 2/3 the flux used to create the image. With an energy resolution of 1 keV, the background would be reduced by over an order of magnitude, providing a much better image of the Np location.

Energy resolution can also be used to see deeper into a complicated object. In travelling through overlying material some of the gamma-rays emitted by an object will Compton scatter, changing direction and losing energy. This acts much like a diffuser in front of a light bulb, blurring the image of the material. If one can generate an image using only the radiation in an emission line then one will obtain a clear image. An example of this is shown in figure 3 where radiation is sent through two mean free paths of material close to a radioactive source.

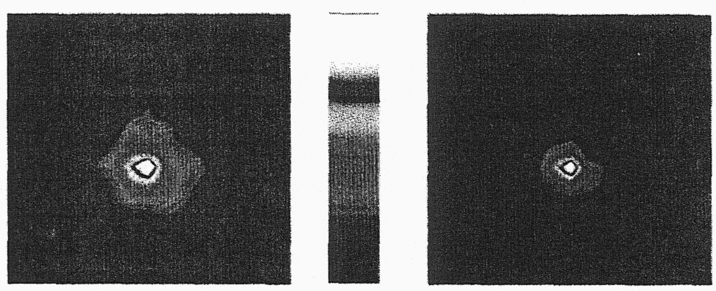

Figure 3. Image of a point source through two mean free paths of shielding. The left image uses all data, the right image uses only the photopeak data. Source intensity increases vertically on the color bar.

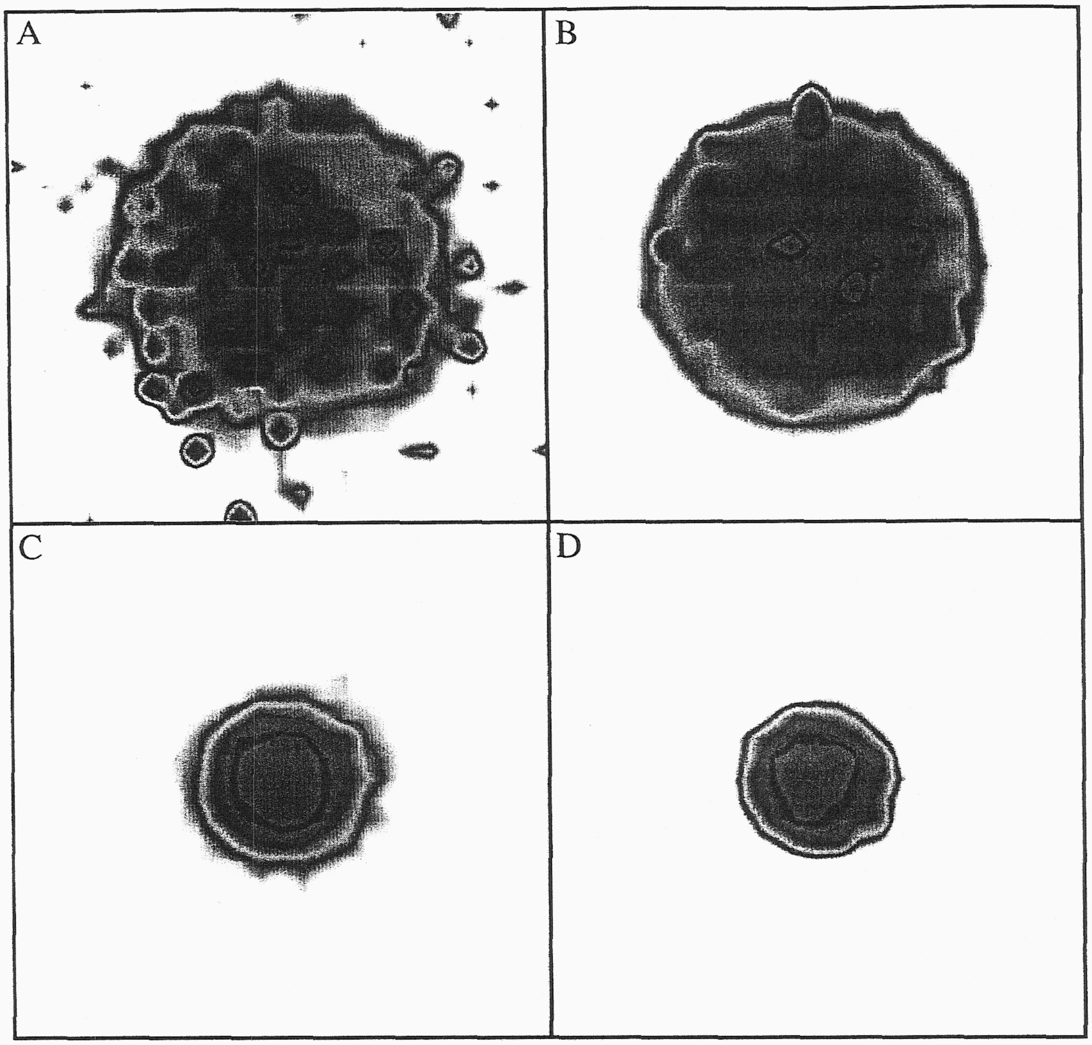

Figure 4. Simulated images of the sources described in the text. A and B are of the large uranium piece (186 keV), C and D are of the plutonium piece (375 keV) which is behind the uranium. The images on the left are based on NaI energy resolution while the images on the right use germanium energy resolution. The NaI images have 1.5 times the integration time of the germanium images. (False color intensity is the same as figure 2.)

The image on the left is generated with all of the detected radiation, while that on the right uses only events in the photopeak. The reduction in the scattered radiation around the point source is obvious.

To demonstrate the improved performance possible with a germanium based imager we have performed an MCNP calculation of a source including two isotopes of fissile material. In the simulation a self-opaque, circular, ^{239}Pu piece 6 cm in diameter is placed behind a 0.5 cm thick, 17 cm diameter enriched uranium piece, both placed inside of a 24 cm cubic box packed with organic packing material. The whole assembly is placed behind a concrete wall 10 cm thick. A pinhole image is collected with a detector at one meter from the source based on two energy bands, one at 186 keV the other at 375 keV. These represent the major emissions of the two radioactive materials.

The width of the energy windows were selected to match either a NaI based or a Ge based detector system. The improvement in image quality is readily apparent in figure 4 where the images collected at the two different energy resolutions are shown. Note that the integration time of the NaI images represents 1.5 times that of the Ge based images.

In addition to improved image quality, enhanced energy resolution can increase the value of measurements in other ways. To obtain detailed isotopic composition of fissile materials requires careful spectral analysis of data obtained with high energy resolution. The analysis requires knowledge of the measurement geometry to correct for self attenuation and attenuation by overlying materials. In many instances, especially in field situations, sufficient geometric knowledge is not available, requiring additional measurements and or estimates of unknown quantities.

With an imager possessing high spectral resolution one can perform the isotopic analysis on a pixel-by-pixel basis. This greatly simplifies the analysis since one no longer needs to know the source shape (other then thickness for self attenuation corrections which come out of the analysis.) In addition, information on the overlying material can also be obtained on a pixel-by-pixel basis. With the known relative strengths of emission lines separated in energy from the same isotope, one can perform gamma-gauging to determine the amount and average z of the overlying material.

System design

The imager uses a coded aperture, indirect, imaging technique[6] coupled to a unique two-part, position-sensitive, germanium detector. The detector takes advantage of the fact that Compton scattering is the predominate interaction mechanism of gamma-rays at high energies in germanium. A one centimeter thick, cross-strip, planer detector is followed by a thick coaxial detector. At low energies the planar detector solely determines the energy and location of an event. At higher energies, the gamma-ray will likely scatter and we use the cross-strip front detector to determine the location of the scatter and then use the coaxial detector to absorb the scattered radiation. The sum of the energies in the two detectors determines the energy of the event. Thus, the optimal imaging performance is different at different energies. Based on the summed energy of each event we can require different divisions of energy between the two detectors to enhance the overall performance.

The planar detector will be one centimeter thick with the electrodes on either side of the detector divided into 40 strips on a 2 mm pitch. The direction of the strips will be orthogonal between the two sides to provide x-y position information. Energy information will be collected on the side of the detector that is at ground potential. The location of an event will be determined by the location of the strip on each side of the detector that collects the charge. The coaxial detector will be selected to fully cover the area of the planar detector. Both detectors will be mounted in a single cryostat.

Performance Simulations

To determine the performance of this detector design we have performed Monte Carlo simulations of the system response to parallel gamma-rays from off-axis point sources of Pu and U. The simulations included a 19 x 17 URA[6] coded aperture imaging optic with 4 mm pixels in front of the detector so that system performance as related to imaging could be assessed. The planar detector had a 2 mm pixelation (to properly oversample the pattern) and the event location was determined by the weighted average of all energy deposited in this detector. This simulates the effect of

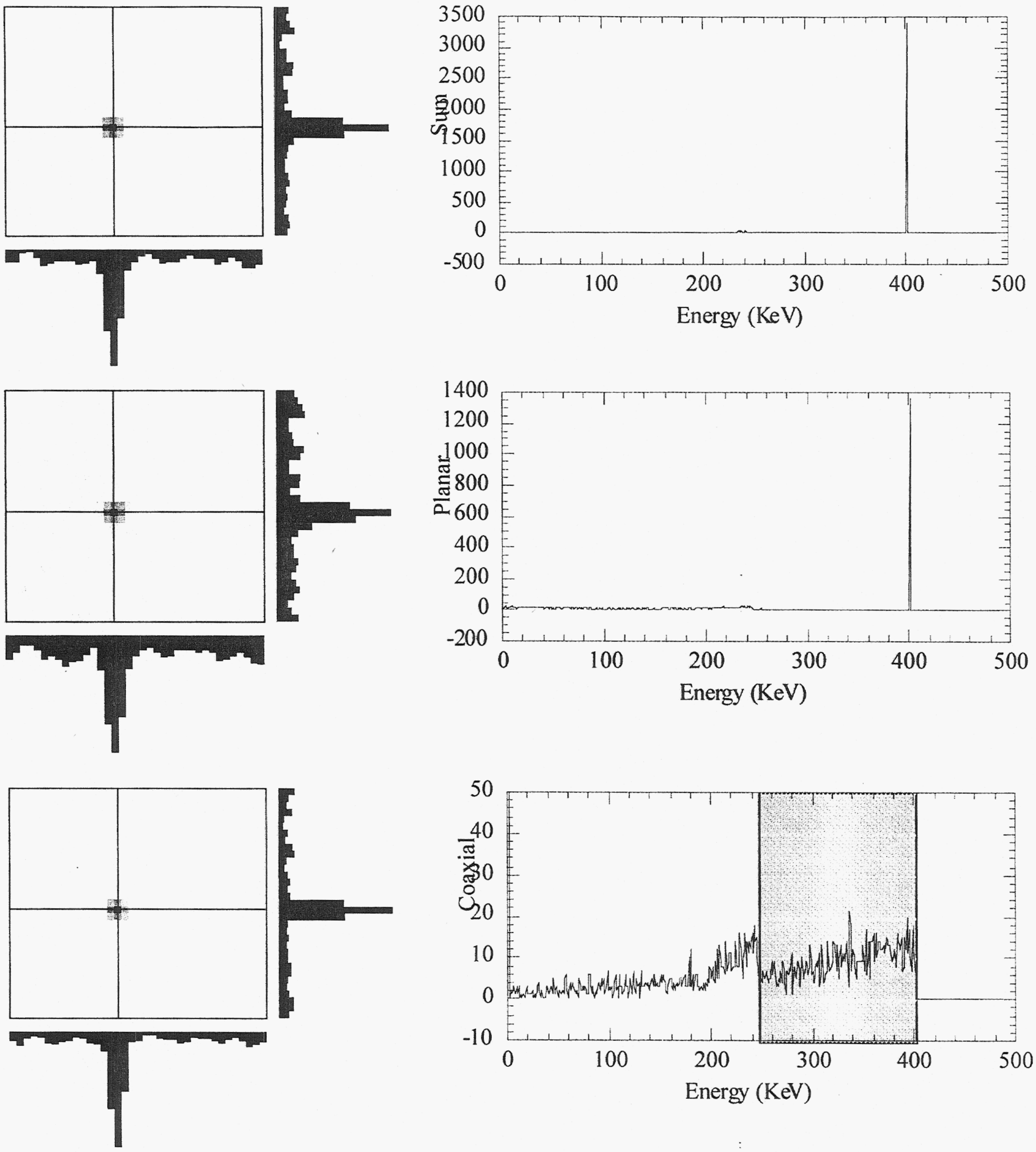

Figure 5. Simulated detector response to off-axis, 400 keV source. The spectra on the left are for the summed (top), planar (middle) and coaxial (bottom) detector energies. The images on the left are the reconstructed images using a cut on the 400 keV sum line (top), the planar 400 keV line (middle) and 400 keV sum plus shaded region in the planar spectrum (bottom). The bar graphs on the sides of the images are the pixel counts along the cross hairs. The signal to noise ratio can be most easily inferred from the peak value to background levels in the bar graphs.

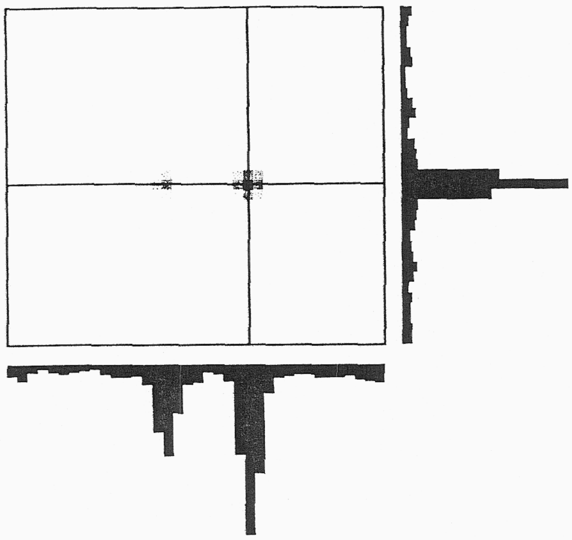

Figure 6. Image obtained with the simulation data for both sources combined.

distributed energy depositions such as occur if the gamma-ray Compton scatters and remains within the planar detector and thus results in "erroneous" position determinations (the desired location is the point of the first interaction.) Each event included the location in the planar detector and the energy deposited in the planar and coaxial detectors. The effects of finite energy resolution were ignored other than through the use of 1 keV wide energy bins. The events were then processed through an analysis routine as would occur in actual use. Each event was passed through energy cuts based on the planar, coaxial and sum energies and, if kept, binned into a 2-dimensional position histogram. This was passed through a standard cross-correlation routine to retrieve the coded aperture encoded image.

The optimum energy windows clearly reflect the physics of the gamma-ray interactions within the detector. This is most obvious in the 400 keV case. In figure 5, the energy spectra and cuts are shown on the right for the images on the left side of the figure. The bottom image is cleanest. It uses energy cuts on the sum energy of 400 keV and events above 245 keV in the coaxial detector. These cuts represent events which undergo a single Compton scatter in the planar detector. It is interesting

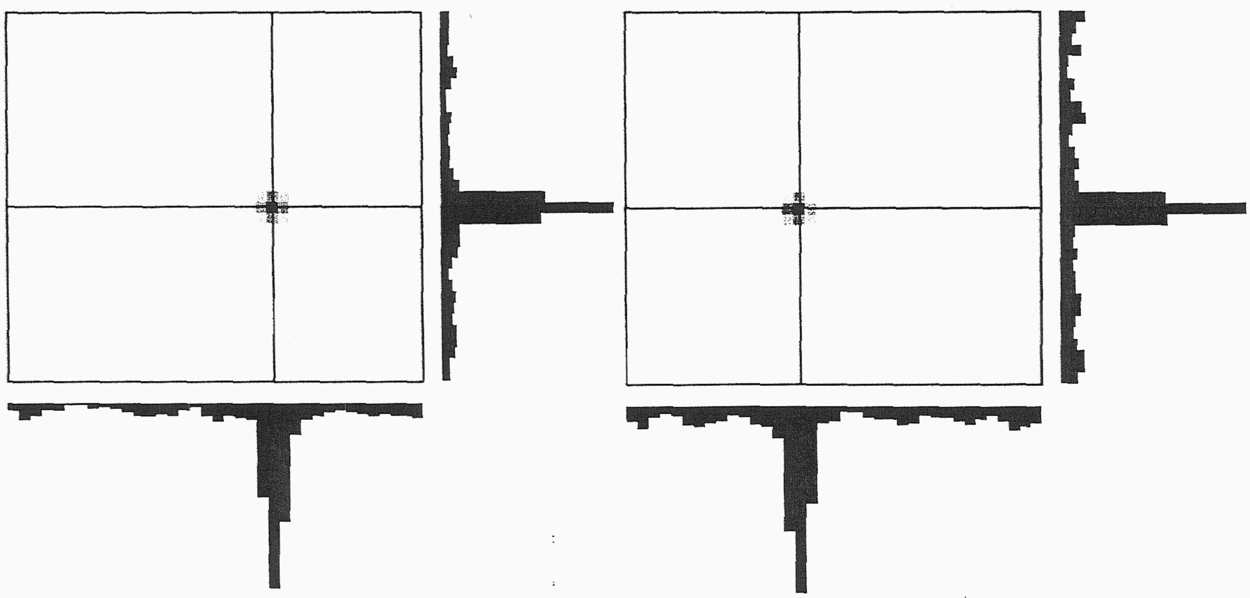

Figure 7. Images obtained using the same data set as in figure 6. On the left energy cuts to accept uranium data are used, on the right the energy is restricted to plutonium values. The energy cuts effectively show only the element of choice.

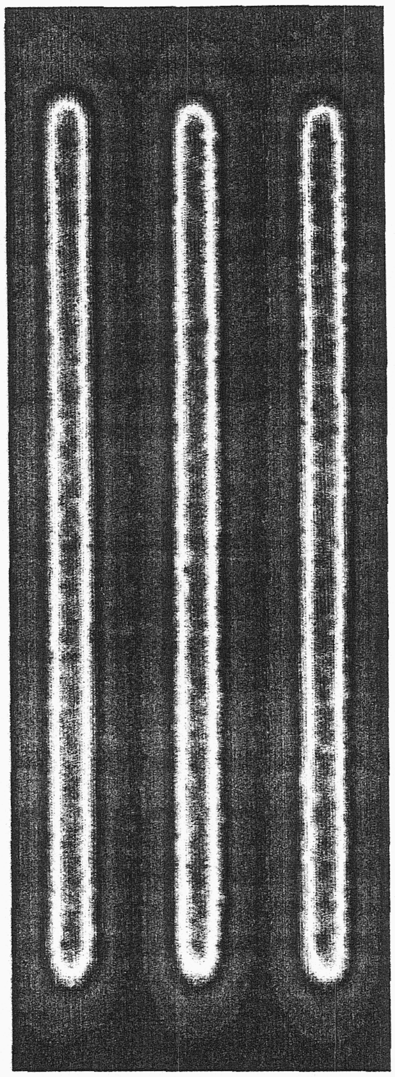

Figure 8. 80 keV scan of prototype detector. Only events registering in the outer and center strip are shown.

to note that the "obvious" choice of photoabsorptions in the planar detector gives the relatively poor middle image. This is not surprising since these events will have a high probability of multiple site interactions in the planar detector and hence have the position misattributed.

For the source at 186 keV the opposite is the case. Almost all of the events represent full deposition in the planar detector. Although presumably a significant fraction of these events are actually Compton scatters, the range of the low energy scattered photon is short enough that it is unlikely to leave the pixel where the interaction occurred.

In figure 6 we present the combined data for both sources without any energy cuts. Both sources are clearly visible. The effectiveness of the energy resolution is seen in figure 7. In the left image a tight cut has been placed on the 186 keV line and the plutonium source disappears. In the right image the optimum plutonium cuts have been used and the uranium disappears. When the optimum energy cuts are selected for the two images the detector system shows a net quantum efficiency of 36% at 186 keV and 8% at 400 keV. This number is exclusive of the coded aperture transmission which is 50%.

A careful look at the images shows some smearing in the x-dimension. This is due to the finite thickness of the planar detector. The gamma-rays enter at an angle and interact throughout the depth of the detector, thus providing a different focal length. This can be removed by correcting for the depth of interaction which we will obtain by comparing the arrival time of the signal at the top and bottom electrodes of the planar detector.[7]

Prototype detector tests

We have built and tested a first prototype one-sided strip detector. This instrument has 5 strips, 3.5 cm long, on a 2 mm pitch produced on a 5 cm diameter, 1 cm thick, germanium piece. The strips were made using amorphous-silicon deposited on the surface followed by aluminum metalization. We tested the uniformity of this device by an automated scan on a 250 μm pitch using a ^{133}Ba source collimated to give a beam ~ 1.5 mm in diameter. The location of an interaction was assigned to the strip with the most charge deposited. A false color plot of the number of counts versus source position for the 80 keV line is shown in Figure 8. In the image, only events attributed to the outer and central strips are shown to avoid the blurring caused between neighboring strips by the relatively wide beam. The results clearly show the uniformity of the detector response over its full surface. The strips are very uniform in size and perform equally well along their entire length. Based on these results we are just now completing a larger prototype cross-strip detector with 19 strips on each side.

Conclusion

The advantages of a gamma-ray imager with high energy resolution can be clearly seen in both simulations and performance extrapolations of extant imagers with modest energy resolution. We are building such an instrument based on a unique, two-part detector system. Simulations indicate that performance of the combined detector will provide good spatial resolution over a wider energy range than would be possible with a simple, single, position-sensitive detector. We have demonstrated that a prototype planar detector will meet our specifications and are just now completing a larger 19 x 19 strip detector.

Acknowledgments

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